

Penrose At Work

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ABSTRACT

If a supermassive black hole has some material orbiting around it at close to its innermost stable circular orbit (ISCO), then, when it plunges into a second supermassive black hole, the orbiting material has a velocity dispersion of order of speed of light about the orbital velocity of its host black hole. It becomes plausible that some of the orbiting material will be “catapulted” to the negative-energy ergosphere orbits of the second black hole at the plunge. This may provide an astrophysically plausible way to extract energy from the black hole, originally suggested by Penrose.

Subject headings: Methods: analytic, Black Hole, Gravitational Radiation, Accretion Disc, Jets

1. Introduction

Bardeen et al. (1972, B72 hereafter) show that one need an extra $v \sim 0.5c$ relative velocity boost after the plunge in order for the inbound debris to reach the ergosphere negative-energy orbits, to ultimately extract energy from the negative-energy orbits to be carried away by the outbound debris. Note that, while for a Kerr black hole the “apparent” radii of the event horizon, the photon orbit and ISCO (r_{ms}) on a prograde orbit are the same in the Boyer-Lindquist coordinates, they are separate in proper coordinates and their energies are distinctly different. For example, for a Kerr black hole, the orbital velocity at ISCO is $0.5c$ (not c) and the minimum energy of a plunge orbit that results from decay of a bound stable orbit is $3^{-1/2}mc^2$ (where m is the mass of the orbiting particle). Thus, in order to get to the negative-energy ergosphere orbits, the orbiting particle at ISCO need to cross over this velocity gap of $\geq 0.5c$. This condition was deemed to be astrophysically unlikely (B72).

We suggest here that, when two black holes merge, if one or both have orbital material at close to their respective ISCO, then some of the orbital material may be able to “jump” over this velocity gap of $\geq 0.5c$ to land in the ergosphere negative-energy orbits, while portion of the orbiting material that escapes may be able to extract energy from the black hole via

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the Penrose (1969) process at the expense of the rotation of the black hole (Christodoulou 1970).

2. Orbiting Matter Around Supermassive Black Holes

Our subsequent argument, in a large part, hinges on the assumption that at least some SMBH are Kerr black holes, because only their ISCO orbits are energetic enough to possess orbiting matter with a velocity dispersion equal to c . This is supported by at least two observational lines of evidence: the observational inference of high radiative efficiency of luminous quasars of $\epsilon \sim 0.2$ (e.g., Yu & Tremaine 2002) and X-ray observations of iron K line profiles (e.g., Iwasawa et al. 1996). Theoretically, Kerr (or near Kerr) SMBH are fairly easily reached by gas accretion (e.g., Volonteri et al. 2005). The existence of accretion gas around SMBH is beyond any reasonable doubt, given the fact that we see quasars shine and there is no reasonable alternative to SMBH accretion.

We shall discuss briefly the possible mix of the matter that may be orbiting SMBH in the inner region; in other words, if things other than gas, such as stars or dense stellar debris, also exist there that are sufficiently long-lived. We shall only consider solar-type stars subsequently. Compact objects such as neutron stars and white dwarfs are always swallowed whole by the SMBH of mass of interest here and we assume that they do not produce astrophysically tangible signals (even if they were launched from the center with very high velocities). The tidal disruption radius for a solar-type star of mass m_* and solar radius r_* is

$$r_t = (M/m_*)^{1/3} r_* = 1.1 M_8^{-2/3} r_s, \quad (1)$$

where $M_8 = M_{\text{BH}}/(10^8 M_\odot)$ and $r_s \equiv 2GM/c^2$ is the Schwarzschild radius. Equation (1) merely states the well known fact that $M_8 \geq 1$ SMBH swallow solar-type stars whole, but smaller SMBH tidally disrupt solar-type stars and are predicted to produce a distinct class of optical-UV flashes that have now been observationally confirmed (e.g., Gezari et al. 2009). It seems likely that, for SMBH with M_8 sufficiently smaller than one, the stellar debris from tidal disruption that becomes bound to the SMBH is gasified through a variety of processes (distortion, compression, precession, possibly nuclear flash and ultimately shocks) and accreted by the SMBH in a relatively short period of time (e.g., Rees 1988). Thus, it may be that there is not a significant amount of stars or stellar debris orbiting $M_8 < 1$ SMBH at $\sim r_{\text{ms}}$. We will now turn our attention to SMBH with $M_8 > 1$, in light of the strong observational evidence of their existence at the center of every giant elliptical galaxy (e.g., Richstone et al. 1998).

For SMBH of $M_8 \geq 1$ three primary routes may be able to capture a star without having to severely damaging it. A star on a low angular momentum parabolic orbit may lose its

orbital energy through repeated pericenter passages to be eventually captured. In order to be captured to an orbit of radius r , it needs to lose an amount of orbital energy equal to $mv_{\text{orb}}^2/2$. Under the assumption that the star is not destroyed (e.g., not puffed up to become a giant), the maximum rate of energy loss may not exceed its luminosity L_* , which translates to a tidal capture timescale t_{tc} being

$$t_{\text{tc}} = \frac{m_* v_{\text{orb}}^2 / 2}{L_*} = 142 \frac{r_s}{r} t_*, \quad (2)$$

where t_* is the lifetime of the star and $L_* t_* = 0.007 m_* c^2$ is assumed. This seems too long to be interesting, given that the star also has to have a pericenter distance not too much larger than r_s to experience significant tidal effect for $M_8 \geq 1$ SMBH (see Equation 1) and our assumed dissipation rate is likely on the generous side already. Of course, if the star gets overheated thus expands, the envelope region that is puffed up would be tidally stripped off to become “gas”.

Interaction between the SMBH with a stellar binary may allow one member of the binary to be captured to a bound orbit around the SMBH. The tidal capture radius through this three-body interaction is

$$r_{\text{bin}} = (M/m_*)^{1/3} a = 1.1 M_8^{-2/3} (a/r_*) r_s \quad (3)$$

(e.g., Hills 1988), which is larger than the tidal radius of a single star (Equation 1) by a factor of a/r_* with a being the semi-major axis. This factor, possibly substantially greater than unity, allows $M_8 \geq 1$ SMBH to be able to capture stars, although the exact rate depends on too many factors to be certain. During the merger of two massive galaxies each hosting a SMBH, it is possible that a significant number of stars (some fraction of them are binaries) may be driven into low energy orbits to reach the inner regions of each SMBH, given the significant amount of torque exerted by one galaxy on the other.

Repeated interaction between stars and an accretion disc around the SMBH may also bring the star to a bound orbit. In fact, Syer et al. (1991) show that for $M_8 \geq 1$ SMBH, star-disc drag may become the dominant capture mechanism.

Given these considerations, it seems that SMBH of $M_8 \geq 1$ with an accretion disc (i.e., luminous quasars) could possibly have both gas and stars at $\sim r_{\text{ms}}$, while $M_8 < 1$ SMBH may carry a disc that is mostly composed of gas. What might happen to stars embedded in an accretion disc is a subject beyond this study. We shall only note two points. First, for a star of mass m on a circular orbit at radius r around a SMBH of mass M , the orbital decay time scale due to its own gravitational radiation is

$$t_{\text{gr}}(r_s) = \frac{5}{256} \left(\frac{c^5 r^4}{G^3 m M (m + M)} \right) = 512 M_8^2 m_0^{-1} (r/r_s)^4 \text{yr} \quad (4)$$

(Peters 1964), where G is the gravitational constant, c is speed of light and $m_0 = m/(10^0 M_\odot)$. Thus, if the supply rate of solar-type stars to regions of $r \sim r_s$, from either decay of outer orbits and/or directly captured by some processes, is larger than $\sim 10^{-3}\text{yr}$ around an $M_8 \geq 1$ SMBH, one should expect to see some accumulation of solar-type stars near the innermost stable circular orbit r_{ms} . Other drag process experienced by stars or dense debris, such as by the accretion disc, is likely to be less strong than the gravitational radiation drag at $\sim r_{ms}$. For our purpose, it suffices that it is astrophysically plausible that SMBHs of $M_8 \geq 1$ prior to their merger possibly carry stars or stellar debris as well as gas in their inner orbits. Second, for $M_8 \sim 1$, the orbiting bound stars may be significantly deformed or disrupted approaching r_{ms} , thus producing stellar debris orbiting at $\sim r_{ms}$. If that happens, the velocity dispersion of the debris will be of order $v_*/c \sim (1000 \text{ km/s})/(3 \times 10^5 \text{ km/s}) \ll 1$. Therefore, the debris would be confined to a relatively narrow range in radius following the disruption.

3. Penrose Process at Work

Consider the inspiral of the two Kerr SMBH, M_1 and M_2 ($M_2 \leq M_1$), via gravitational radiation, with only M_2 (for simplicity) carrying a disc of gas and/or stellar debris orbiting at $r \geq r_{ms}$. We assume that all angular momentum vectors are parallel and all orbits are on the same plane. When M_2 arrives at r_{ms} of M_1 , one finds that at any instant some material is moving at the same direction as the orbital velocity of M_2 around M_1 with a relative velocity of $0.5c$, while some other material is moving at the opposite direction to the orbital velocity of M_2 around M_1 with a relative velocity of $0.5c$. Still, there is some other material that is in-between. Assuming at least some debris are still on some elliptical-like orbits (may or may not be closed), given that the relative velocity of the debris around M_2 spans the whole range from $-0.5c$ to $0.5c$ relative to the orbital velocity of M_2 about M_1 , it seems plausible that at least some of this material is able to fill in the required velocity gap of $\geq 0.5c$ relative to the orbital velocity at r_{ms} of M_2 to reach the ergosphere negative-energy orbits of M_1 . Assuming that the part of the orbiting material that reaches the ergosphere negative-energy orbits is able to communicate with the remainder of the material that eventually escapes, the originally proposed Penrose (1969) process to extract energy from the SMBH may become possible. However, caution should be taken. It may be that, when the two SMBH get that close, the assumptions on which our simple argument is based break down. The primary assumption is that the orbiting material at $\sim r_{ms}$ around M_2 , at least some of it, manages not to plunge into M_2 during the process in the presence of a nearby M_1 , but instead plunges to a minimum-energy orbit of M_1 . The other assumption is that the orbiting material around M_2 has not lost the velocity dispersion of c that it had at ISCO, when plunging into M_1 . The second assumption at least seems feasible, because it is rather unlikely that during the short time of the plunge one is able to “remove” or dissipate the velocity dispersion of order the speed of light for the orbiting material around M_2 . On the contrary, it would seem plausible

that, during the plunge, en route to the event horizon, the velocity dispersion of the orbiting material may be further increased. Detailed black hole merger simulations (e.g., Pretorius 2005), carrying some extra amount of orbiting material, will be necessary to provide some insight.

If what is outlined above really happens, what the escaping material that is leaving with a total energy higher than its initial total energy (but with reduced rest mass) will look like is just a guess at this time, in the absence of detailed simulations. But it is conceivable that the debris may form a relativistic jet or, strictly speaking, a mixed flow of gas and stellar debris moving at (nearly) the speed of light, in a fashion perhaps not unlike what was suggested earlier (Wheeler 1971). If the escaping amount of material is substantial and especially a substantial fraction of that is stars or dense stellar debris, the flow may be quite “bulletstic” hence would remain cruising in a straight line, like a jet, for a while.

4. Conclusions

We have argued that it is astrophysically plausible that Kerr SMBH carry a significant amount of material (gas and stars or stellar debris) in the inner region close to the innermost stable circular orbit, after their host galaxies merge. The orbiting matter at ISCO has a velocity dispersion equal to the speed of light about the orbital velocity of their host SMBH. As a result, we suggest that, when the two SMBH merge, some of the debris may be able to jump over the velocity gap between the ISCO orbit and negative-energy ergosphere orbits. If that indeed happens, we would have found an astrophysically plausible way to tap into the vast rotational energy reservoir of SMBH via the Penrose process.

This work is supported in part by grants NNX08AH31G and NAS8-03060.

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